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Synaesthesia is linked to a distinctive and heritable cognitive profile

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This study argues that there exists, in the general population, a distinctive profile of cognitive traits that predisposes people to develop synaesthesia (termed a 'synaesthetic disposition'). This consists of more vivid mental imagery, better episodic memory, and greater attention-to-detail (amongst others things). Using a machine-learning classifier, we show that it is possible to distinguish synaesthetes from others using only standard cognitive and personality measures. Importantly, people with multiple forms of synaesthesia have a more distinctive profile (i.e. they can be more accurately classified). This suggests that whilst the presence/absence of synaesthesia is dichotomous, the underlying causal mechanisms are continuous. Moreover, we provide evidence that the cognitive profile constitutes a heritable endophenotype. Non-synaesthetic relatives of synaesthetes are cognitively similar to synaesthetes. This provides new insights into why synaesthesia might have evolved (i.e. it is possible to have the cognitive benefits of synaesthesia in the absence of the anomalous experiences). The notion of a synaesthetic disposition represents a novel, quantifiable individual difference in cognition/personality. This paves the way for determining if this is linked to a distinctive pattern of clinical vulnerabilities.

For someone with synaesthesia the number 5 may be yellow, the word “justice” might taste fruity, or the months of the year may be visualised as a 3-dimensional landscape. Despite the renewed research interest in synaesthesia since the turn of the 21st Century, many of the big questions remain unresolved. Why do some people have synaesthesia and others do not? Does it reflect the mere retention of childhood associations, or does it reflect a distinct brain-type akin to a neurological ‘condition’ [1]? Is synaesthesia continuous with neurotypical cognition such that we are all synaesthetes (albeit to differing degrees)? Why does synaesthesia exist? Is it epiphenomenal, or is it functional/adaptive in some way [2]? On hearing detailed descriptions of synaesthesia, the philosopher William James noted how the “extraordinary diversities of inner scenery” in synaesthesia pose a challenge to any unitary theory of intelligence as a “purely logical” or abstract entity [p.92 3]. James’ challenge remains unanswered today.

Most of the previous discussion as to how synaesthesia is (or is not) related to neurotypical cognition/perception, has centered around a discussion of cross-modal correspondences [e.g. 4, 5]. Cross-modal correspondences are systematic tendencies to link together seemingly unrelated sensory properties such as taste-shape (sour is pointy), and pitch-lightness (high-pitch is lighter) [6]. The debate has focussed on whether synaesthesia reflects exaggerations of normal correspondences, whether they are conscious versions of normally implicit correspondences, and so on. In a recent theoretical paper, Ward [7] offered a different framework for understanding the relationship between synaesthesia and neurotypical cognition that is not focussed around the cross-modal correspondence debate. Specifically, a distinction is made between synaesthesia and the causes of synaesthesia (termed a ‘synaesthetic disposition’). The synaesthetic disposition is assumed to reflect neurocognitive differences brought about by differences in genetic make-up (synaesthesia has a genetic component [8]). The synaesthetic disposition is assumed to be continuous such that people have it to a greater

or lesser extent (i.e. it links synaesthetes to non-synaesthetes). The greater the synaesthetic disposition then the greater the probability of developing synaesthesia and the greater the probability that synaesthesia will develop multiple times in the same individual. In this way, the number of types of synaesthesia a person has may act as a proxy marker for their underlying synaesthetic disposition. The presence/absence of synaesthesia is assumed to be dichotomous (people have it or they do not) but, for people who have it, it may vary in degree (e.g. number of types). In this account, cross-modal correspondences influence the way synaesthesia is manifested but they are not causal.

The separation of synaesthesia (a special entity defined by atypical experiences) from a synaesthetic disposition (a particular kind of individual difference) accounts for existing data and makes testable predictions. It may be that many of the cognitive differences linked to synaesthesia are not due to the presence of synaesthesia per se (e.g. experiencing numbers as coloured), but rather to the accompanying ‘brain-type’ or ‘cognitive style’ that predisposes to the emergence of synaesthesia in the first place [7]. People with synaesthesia have been shown to have a number of cognitive differences including more vivid mental imagery across multiple senses [9], better performance on tests of episodic memory [10] and creativity [11], more openness to experience on personality questionnaires [12], and a greater tendency to have traits linked with autism [13]. Although not all of have not been examined in this way, in many cases there is evidence that these differences extend across types of synaesthesia and are related to the number of types of synaesthesia experienced. In this view, it may be the synaesthetic disposition which is functional, and adaptive from an evolutionary perspective. By contrast, the synaesthetic experiences themselves may either be epiphenomenal or may have more circumscribed effects on cognition (depending on the particular type of synaesthesia experienced, rather than the presence of synaesthesia per se). A testable prediction is that some non-synaesthetes may demonstrate a high synaesthetic disposition without developing

synaesthesia and that this should be detectable in the non-synaesthetic relatives of synaesthetes. These people should have cognitive and structural/functional brain differences that resemble synaesthetes (or, at least, they should be intermediate between synaesthetes and opportunistically sampled non-synaesthetes given that first-degree relatives share half of their genes with a synaesthete). A recent study demonstrated some brain connectivity differences in non-synaesthetic relatives of synaesthetes [14], but nothing is known about their cognitive profile.

Although many cognitive and personality differences have been linked to synaesthesia, the current evidence falls short of the claim that synaesthetes have a distinctive cognitive profile. For instance, in the case of episodic memory a meta-analysis shows a Cohen's d of around 0.6 [10] which suggests a large overlap of scores that would be unreliable diagnostically. Other effect sizes linked to synaesthesia rarely exceed that value. However, one possibility is that it is the pattern across multiple different measures of cognition that is distinctive (i.e. the co-occurrence of enhanced episodic memory with vivid imagery plus autistic traits etc.). This can be tested using machine-learning approaches (e.g. k-nearest neighbours) that make binary classifications (synaesthete v. non-synaesthete) on patterns of multi-dimensional data (test scores, questionnaire scores). In this study, we determine whether synaesthetes and non-synaesthetes can be accurately classified based solely on standard measures of cognition and personality and we test whether this constitutes evidence for a hypothetical synaesthetic disposition such that the classification accuracy depends on (a) the number of types of synaesthesia experienced and (b) being genetically related to a synaesthete.

Method

We report how we determined our sample size, all data exclusions (if any), all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

Participants

The participants consisted of 101 synaesthetes (mean age = 34.713 years, S.D. = 13.098; 86 females/13 males/2 other) and 100 non-synaesthetic controls (mean age = 33.860 years, S.D. = 12.477; 80 females/20 males) matched for age and gender. These sample sizes go beyond what is necessary for detecting medium effect sizes ($d=0.6$, $\alpha<.05$, $\beta<.05$) which was necessary to recruit sufficient relatives (see later post-hoc power calculation) and to explore variation within the synaesthetes. The synaesthetic participants had previously volunteered for research via our website (www.sussex.ac.uk/synaesthesia) but had not taken part in any previous testing (except for the purpose of diagnosing synaesthesia). When volunteering, they completed a brief tick-box questionnaire that describes the types of synaesthesia that they have. For present purposes, the following five types of synaesthesia were considered: grapheme-colour, sequence-space, tickertape (visualising words when hearing them), music-colour, and lexical-gustatory. These were based on previous research using this classification [13], and chosen on the basis of tapping a diverse set of inducers and concurrents. Based on this scheme there were $N=37$ synaesthetes with 1 kind, $N=25$ synaesthetes with 2 kinds, $N=24$ with 3 kinds, $N=13$ with 4 kinds, and $N=2$ with 5 kinds. Synaesthetes were verified using either a test of grapheme-colour consistency [15], or sequence-space consistency [26], depending on what they reported. The control group had to confirm that they did not have synaesthesia (after being given a brief description and some example images) and that they were not aware of anyone in their immediate family with synaesthesia.

The relatives, N=25, were recruited via the synaesthetes (who were forwarded a separate link). The test was the same except they were asked who had referred them and confirmed their relationship to them. They were asked to recruit relatives who did not have any kind of synaesthesia and the relatives were asked to confirm that they did not have synaesthesia (after being given a brief description and some example images). Only first-degree relatives were included and consisted of 9 fathers, 7 mothers, 1 son, 3 daughters, 3 brothers, and 2 sisters. The mean age was 53.120 (S.D. = 17.362). As this sample tended to be somewhat older and more male, they were additionally compared to a subset of N=25 synaesthetes and N=25 controls matched exactly for gender and not differing significantly in mean age (mean age of matched synaesthetes = 50.24, S.D.=12.89; mean age of matched controls = 49.44, S.D.=8.74).

Materials and Procedure

There were four questionnaires and three tasks that were presented online (www.testable.org). These were all brief and the total testing time was less than 25 minutes. The memory test consisted of a learning phase and test phase that were always the first and last tasks that a participant did (i.e. to maximise time between learning and testing), and the others were randomly ordered in between (with a different order for each person).

The learning phase of the memory task was described as a test of language (i.e. so participants were unaware that their memory was being tested). They were shown 24 concrete nouns (e.g. “monkey”) of 5-7 letters in length and, for each item, they were asked to indicate by button press whether the word contained a letter E or not. There was a 2 second time-out after which the next word appeared. In the final test, they were shown 48 words (24 old and 24 new) with new words also being concrete nouns of 5-7 letters. Words were presented one at a time in random order and participants indicated with a button press one whether they believed the item to be old (i.e. from the first ‘language test’) or new, and their degree of

confidence in their answer on a 4 point scale (very confident, fairly confident, some confidence, guess).

The other two tasks were the Embedded Figures Test (EFT) of local perceptual processing and [13] the Remote Associates Test (RAT) of creativity/convergent thinking [31]. The EFT consisted of 12 items that were displayed until a time-out of 12 seconds (a countdown was displayed in the top right). Participants were shown a black-and-white figure (e.g. a trapezium) with four more complex designs underneath in which the target shape was hidden in only one of them. Participants had to press a button to indicate which design contained the embedded figure. Feedback was provided for the first two items to ensure participants understood the instructions. The RAT also consisted of 12 items displayed for 12 seconds, with a visible countdown, followed by a response box (participants could advance to the response box if they found the answer before the timeout). The items consisted of a triplet of words (cottage - Swiss – cake) for which the participant had to find a connecting word (cheese). Items were taken from a list on the internet (<https://www.remote-associates-test.com/>). Feedback was provided for the first two answers to ensure participants understood the instructions. For each of these tests the dependent variables were accuracy (%) and response times for correct responses (msec).

The questionnaires consisted of: two subscales of the autism quotient [AQ 32], a shortened version of the Glasgow Sensory Questionnaire [GSQ 33], the Ten Item Personality Inventory [TIPI 34] and a shortened version of the Plymouth Sensory Imagery Questionnaire [PSI-Q 35]. The AQ attention-to-detail and social subscales have 10 items each and answered on a 4 point scale (Definitely Agree; Slightly Agree; Slightly Disagree; Definitely Disagree) which were coded 1-4 where a higher score denotes more autistic tendencies (after reverse coding of items as appropriate). These were summed for each person. Example items include “I tend to notice details that others do not” (attention-to-detail) and “I find it difficult to work

out peoples intentions” (social). Ten items from the GSQ were chosen that, in our previous research, had been shown to maximally discriminate synaesthetes from controls (remembering that the current sample is independent from previous ones). An example item is “Do you cut the labels out of your clothes?” and is answered on a 5 point scale (0-4 corresponding to Never; Rarely; Sometimes; Often; Always). The answers are summed for each person. The PSI-Q consisted of two items from each of 5 modalities (vision, sound, touch, taste, smell) with the items chosen by having the highest factor loadings in the original questionnaire. Example items include “Imagine the appearance of... a bonfire” and “Imagine touching... fur” and are scored on a 0-10 scale (0=’no visual impression’ or ’no touch impression’ etc. and 10=’as vivid as real life’). The TIPI consists of ten word pairs that denote the ‘Big Five’ personality traits (Openness, Conscientiousness, Extraversion, Agreeableness, Neuroticism) for example “I see myself as: Open to new experiences, complex”. Half of the items are reverse coded. They are answered on a 7-point scale (Disagree strongly; Disagree moderately; Disagree a little; Neither agree nor disagree; Agree a little; Agree moderately; Agree strongly), thus each trait is given a score between 2 and 14.

Analysis

The k-NN approach was implemented using Matlab based on data from the EFT (accuracy and RT when correct), the RAT (accuracy and RT when correct), PSI-Q (entering each modality separately), the GSQ (total score), the AQ (considering attention-to-detail and social subscales separately), the TIPI (entering each personality trait separately), and memory performance (separate accuracy for old and new items subdivided into confidence bins). Each of these dependent variables acted as a separate dimension that was linearly rescaled to lie between 0 and 1 (the observed minimum and maximum scores for that variable). Each participant was contrasted with every other participant in the set (except themselves) by computing the Euclidean distance between the target person’s scores and everyone else’s

scores. The shortest $k=15$ Euclidean distances were then used to define the composition of that person's 'neighbourhood' (i.e. the extent to which they were surrounded by synaesthetes or controls). This k was based on the common practice of using the square root of the total sample size ($N=201$) rounded to the nearest odd number (to avoid ties). This was then repeated iteratively for each participant using a 'leave one out' procedure (a form of cross-validation). A comparable procedure was carried out with the data from the relatives but such that each relative was contrasted only against the combined set of synaesthetes and controls (i.e. relatives were never compared to other relatives).

Results

As a preliminary analysis, the individual test scores of the synaesthetes are compared against the controls (see Supplementary for full test breakdown). Significant differences were found for accuracy scores on the Embedded Figures Test ($t(199)=2.832$, $p=.005$) and Memory test ($t(199)=2.928$, $p=.004$), with synaesthetes scoring higher. Moreover, synaesthetes self-report greater mental imagery across all senses ($t(199)=3.553$, $p<.001$), greater sensory sensitivity ($t(199)=5.838$, $p<.001$), and heightened attention-to-detail ($t(199)=9.480$, $p<.001$). There were no significant group differences for the Remote Associates Test, personality traits (TIPI), or social difficulties (AQ). It is to be noted that the classification algorithm is not driven solely by those test scores that significantly discriminate synaesthetes from controls. Smaller effects or even non-existent differences may also play a role. This is because the algorithm identifies a pattern across multiple dimensions, and a pattern such as 'good at X but average at Y' might be more informative (i.e. correspond to a more distinctive neighbourhood) than 'good at X' alone or other combinations (e.g. 'good at everything').

Turning to the results of the k -NN classification based on the pattern of scores, Figure 1 shows the probability that a participant will be classified as a synaesthete for both

synaesthetes (grouped according to the number of types of synaesthesia they have) and non-synaesthetes (divided according to whether they are genetically related or not). The sensitivity of a test refers to the probability of a synaesthete being classified as a synaesthete and this was 97% for people with 3 or more kinds of synaesthesia (overall it was 82%). The specificity of a test refers to the probability of classifying a control as a control and here the figure was 65% for non-relatives. The area under the curve (AUC) represents an overall measure of diagnostic acceptability of a measure irrespective of the choice of binary cut-off and here it was ‘good’ at 0.803, but rising to an ‘excellent’ 0.907 for more extreme cases (3 or more kinds versus controls). As a point of reference, the most widely used diagnostic test of grapheme-colour synaesthesia has an equivalent sensitivity, specificity, and AUC of 89%, 88%, and 0.92 respectively [15].

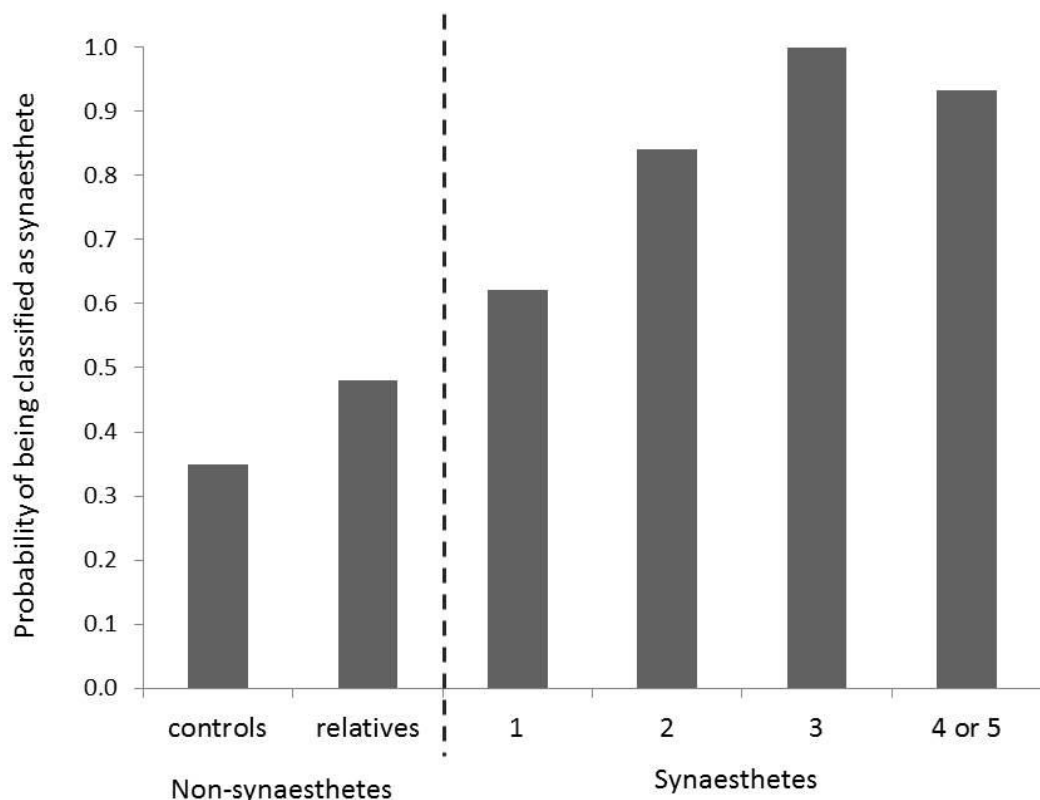


Figure 1. The probability of being classed as a synaesthete based on the pattern of cognitive tests and questionnaire scores. Synaesthetes are sub-divided according to the number of types

that they initially reported (1 to 5) and non-synaesthetes are sub-divided according to their relatedness to a known synaesthetes.

Figure 2 shows the neighbourhood density. Overall, synaesthetes had more synaesthetes in their neighbourhood compared to unrelated controls ($t(199)=8.523$, $p<.001$), and this was a large effect (Cohen's $d=1.208$). Considering the synaesthetes alone, the number of types of synaesthesia a person reports is significantly predictive of neighbourhood density ($r=.386$, $p<.001$). That is, more extreme synaesthetes occupy a more distinctive cognitive niche (they are similar to each other, but dissimilar to non-synaesthetes). Considering the non-synaesthetes, the relatives of synaesthetes differ from non-synaesthetic controls ($t(123)=3.271$, $p=.001$). This is consistent with the idea of a 'synaesthetic disposition' being heritable in its own right (i.e. as an endophenotype) irrespective of the presence/absence of synaesthesia. This result is maintained when comparing the synaesthetic relatives against the $N=25$ age and sex matched controls ($t(48)=3.311$, $p=.002$; mean of relatives = 0.544, S.D. = 0.152; mean of controls = 0.400, S.D.= 0.155). The estimated power was 0.90 ($\alpha=.05$) suggesting that our sample sizes were sufficient to reliably detect this difference (the magnitude of which was not known a priori). The synaesthetic relatives were indistinguishable from the $N=25$ age and sex matched synaesthetes ($t(48)=0.700$, $p=.488$; mean of relatives = 0.573, S.D. = 0.144).

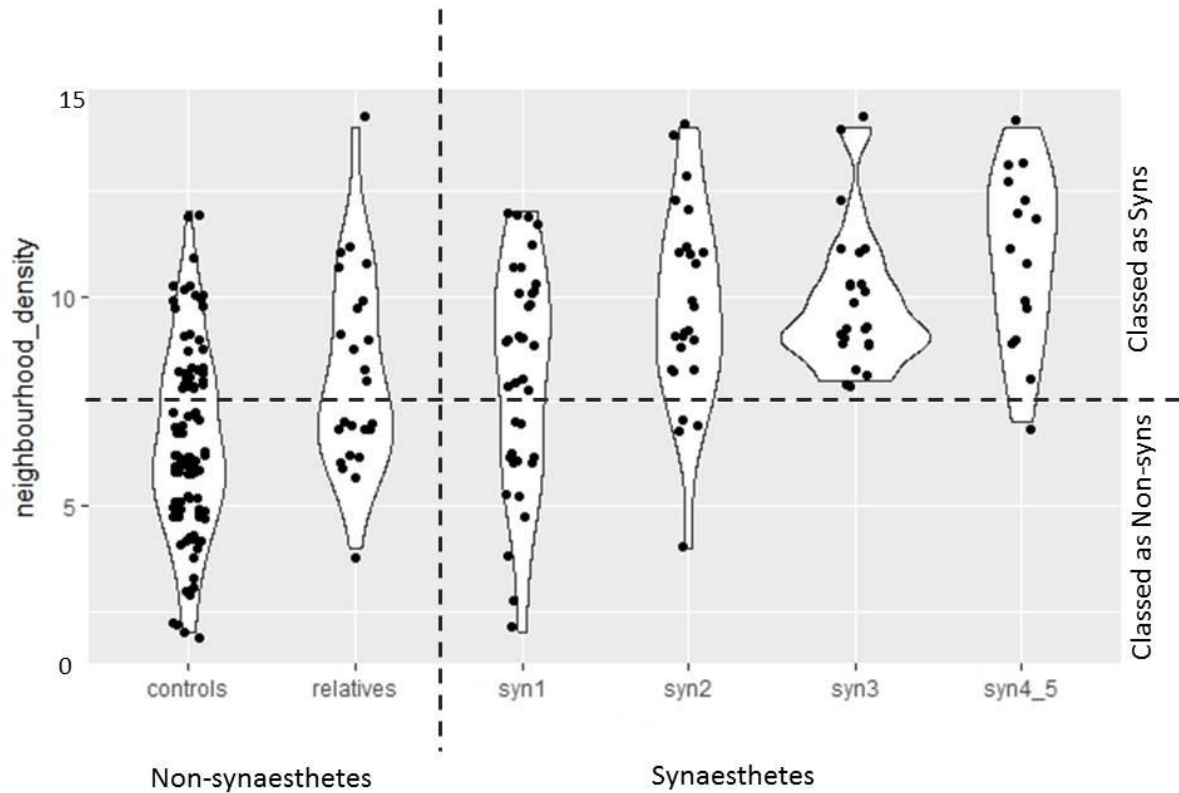


Figure 2. Violin plots showing the neighbourhood density of individual participants as a function of their group. Synaesthetes are sub-divided according to the number of types that they initially reported (1 to 5) and non-synaesthetes are sub-divided according to their relatedness to a known synaesthetes.

Discussion

This is the first study to show that synaesthetes can be discriminated from non-synaesthetes based on brief standard measures of cognition and personality using machine-learning classification. The accuracy of classification was shown to depend on two initially hypothesised variables: the extensiveness of a person's synaesthesia (someone with more extreme synaesthesia has a more distinctive cognitive profile) and whether one is genetically related to someone with synaesthesia (non-synaesthetes who are closely related to a synaesthete

are cognitively different from other non-synaesthetes). The current data broadens the possibilities for genetic mapping of these related traits in families.

This research is consistent with the existence of a particular pattern of individual differences that predisposes people towards differing degrees of developing synaesthesia, which we have termed a ‘synaesthetic disposition’. The fact that it is found, to a degree, in relatives suggests it acts as a predisposing influence rather than being a consequence of having synaesthesia itself. This is a novel construct that, we suggest, has a mixture of benefits (certain cognitive abilities) but also may pose risks (clinical vulnerabilities such as autism). The extent to which the notion of a ‘synaesthetic disposition’ can be reduced to familiar constructs such as intelligence or the broad autistic phenotype is unclear. Tests such as the Remote Associates Test (RAT) are commonly taken as measures of intelligence (although the RAT wasn’t significant in the present study). There are some aspects of being synaesthetic, such as vivid mental imagery, that have no known bearing on measures of intelligence [16] and the relationship between autism and intelligence is far from straightforward [17]. Moreover, synaesthetes tend to do particularly well on tests of episodic memory and relatively less well on tests of working memory [10], whereas working memory is central to most theories of intelligence [18]. To come back to William James [3], if synaesthesia is linked to intelligence then we may need to modify our conceptions of intelligence or – more plausibly – synaesthesia represents a different style of cognitive ability. These cognitive abilities may sit outside of any direct benefits of synaesthesia itself (i.e. afforded by the conscious concurrents themselves), perhaps even to the extent that the synaesthetic experiences are largely epiphenomenal.

Synaesthesia and autism tend to co-occur more than expected by chance, but this appears to revolve around certain symptoms (heightened sensory sensitivity [19]) and subtypes (e.g. savant syndrome [23]). As such, we propose that synaesthesia (or, rather, the mechanisms that give rise to synaesthesia) constitutes a distinctive form of vulnerability to

autism. One can also test whether the synaesthetic disposition predisposes towards clinical symptoms with perceptual characteristics such as hallucinations and flashbacks. There are experimental paradigms that induce something akin to hallucinations in non-psychiatric populations, and these procedures involve synaesthesia-like training between two senses [24]. Are ‘non-synaesthetes classed as synaesthetes’ more susceptible to these effects? Flashbacks are a clinical symptom of PTSD (post-traumatic stress disorder) consisting of involuntary mental imagery of the traumatic event. The presence of synaesthesia is a possible risk factor for PTSD in people exposed to trauma [25]. But note that it is far more plausible that the relationship between synaesthesia and PTSD is due to shared cognitive individual differences (e.g. in mental imagery and memory) rather than the synaesthesia per se (e.g. coloured numbers leading to the retention of trauma). This hypothesis remains to be tested.

There are a number of limitations of the present study. Firstly, some of our measures may have been too brief to be sufficiently sensitive (e.g. the RAT had only 12 items and the TIPI had 10 questions, 2 for each subscale). Another recent study using the TIPI measure of personality also failed to replicate previous findings that synaesthetes score higher on openness to experience [26]. It is to be noted that this shortened measure omits items relating to artistic inclination that may be driving the synaesthetic group difference. Secondly, and perhaps relatedly, the specificity of the classification was worse than the sensitivity: around a third of non-synaesthetes were classed as synaesthetes. This figure may be revised downwards with more extensive testing and/or better classification approaches. However, there are other reasons to believe that this figure will never be very small. With a prevalence of synaesthesia of 4.4% [27] there would be many first-degree relatives of synaesthetes who, under this account, would have a reasonably high synaesthetic disposition. Moreover, there are other phenomena that resemble synaesthesia (and may indeed be types of synaesthesia) that are not especially rare. These include ‘mirror pain’ (prevalence of around 25% [28]) and ‘hearing

motion' (prevalence of up to 22% [29]). Future research should consider whether these are particularly prevalent in controls with a high synaesthetic disposition at which point, of course, we may simply be inclined to label such people as 'synaesthetes'. In short, the concept of a quantifiable synaesthetic disposition is a significant step towards resolving the definitional problem outlined by Simner [30] that there is no independent means of determining which phenomena should or should not be classified as synaesthesia.

An alternative account is that having more synaesthetic concurrents would in itself lead to more cognitive differences (over and above any genetic disposition also found in relatives). But this alternative account would have to explain how, exactly, that happens. For instance, consider vividness of imagery when asked to "imagine touching fur" or "imagine the appearance of a bonfire" (items used here). It is just not clear why something like grapheme-colour synaesthesia would directly have an impact on this, or why having multiple combinations of synaesthesia would either. Instead, more vivid mental imagery may be a predisposing influence to synaesthesia such that the two things tend to go hand-in-hand but, in no way, does having coloured numbers (for example) assist a person to imagine the appearance of a bonfire. This general issue is discussed in Ward [7], and can be explored empirically by considering whether there is any relationship between the types of synaesthesia and the particular cognitive differences manifested (e.g. see [13] for this approach to sensory sensitivity).

In summary, our conclusion is that synaesthesia is linked to a distinctive cognitive profile, with a heritable component, that has hitherto been missed by researchers interested in individual differences. It is distinctive insofar as it can reliably (albeit not perfectly) classify synaesthetes and because it is not readily reducible to existing constructs. The notion of a synaesthetic disposition is also quantifiable. It can be measured by, for instance, the proportion

of synaesthetes who are in one's cognitive neighbourhood. Further research will determine if this measure has clinical relevance.

Supplementary Information

The data and analysis code are archived at osf.io/xk893. No part of the study procedures or analyses was pre-registered in an institutional registry prior to the research being conducted.

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